Passive Mode-Locker Incorporating Physically Exfoliated Graphene for Fiber Ring Lasers

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Abstract: A passively mode-locked fiber laser is realized using an intracavity intensity-modulating effect in multilayered graphene efficiently prepared by taping method. 10.6-MHz pulse trains with 40-dB extinction rate are guaranteed by the physically exfoliated graphene.

OCIS codes: (140.4050) Mode-locked laser; (160.4236) Nanomaterials, (060.3510) Lasers, fiber.

1. Introduction

After the discovery of graphene that has excellent electronic properties originated from the 2-dimensional morphology of carbon atoms, diversified further researches on graphene and its applications have been accelerated dramatically for couple of years. [1,2] With the advantages such as ultrafast operation, low saturable absorption threshold, large modulation depth, and wavelength-independent operation compared to conventional semiconductors or carbon nanotubes (CNTs), graphene has attracted huge technical attention in the field of ultrafast photonics. [3] The excellence of atomic-layer graphene-based saturable absorbers as a mode locker for optical fiber-based subpicosecond pulse lasers has been successfully demonstrated [4]. Graphene saturable absorbers were usually made with a 2-D flat graphene thin film closely attached onto the end facet of a fiber pigtail or a sprayed thin film on a D-shaped fiber [5]. However, the preparation processes of graphene and graphene-based devices still rely on traditional and inefficient approaches that cannot be free from the restrictions of additional transfer process steps and the extremely low yield of graphene. Even a graphene-polymer nanocomposite membrane that was introduced to increase the saturable absorption performance requires the additional transfer step onto a targeted substrate. Note that this additional process must induce huge loss of graphene. [6,7] On the other hand, a dramatically simplified but elegant graphene preparation method based on physical exfoliation of bulk graphite with a strip of scotch tape has been very recently reported [8]. Using a graphene sample obtained with this method, the morphological and electrical properties of the graphene have been well investigated. However, the optical properties of the physically prepared graphene sample still need to be investigated. Moreover, the suitability of the graphene sample for ultra-fast photonic applications as a saturable absorber should be verified.

In this work, we prepared physically exfoliated multilayered graphene, and experimentally investigated its applicability for passive mode-locking of the fiber lasers as a saturable absorber. With the systematic characterization on its optical properties employing atomic force microscopy (AFM) and Raman analysis, we found that the samples had multilayered morphologies ranging from < 1 nm to > 15 nm still inducing the optical intensity dependent absorption modulation. The group velocity dispersion (GVD) property of the graphene samples was analyzed by a high resolution GVD measurement setup to find that the nano-scaled thin layers had negligible GVD unlike the previously reported result [9]. Finally, we carried out laser mode-locking experiments using three taping-exfoliated graphene samples. Successfully, all graphene samples were capable of inducing passive mode-locking in an erbium-doped fiber-based ring laser configuration as saturable absorbers ensuring applicability, functionality, and reproducibility of the physically exfoliated graphene.

2. Graphene layer sample preparation and dispersion characterization

In preparing the multilayered graphene on the end facet of the optical fiber ferrule, a simple and efficient physical exfoliation method was used. The starting material was commercially available highly ordered pyrolytic graphite (HOPG) from SPI Co. The HOPG sample, which had a dimension of 10 mm x 10 mm, was prepared via mechanical cutting. The HOPG flakes were peeled repeatedly using scotch tape to adjust the sample thickness that was optimized for pressing by the substrate. Considering the strong interaction between the contacting surfaces of the graphite and the optical fiber (the amorphous SiO_2) that tended to form a graphite/SiO_2 interface with low interfacial energy, physical exfoliation can be applied to the graphene layer formation on the optical fibers [8].

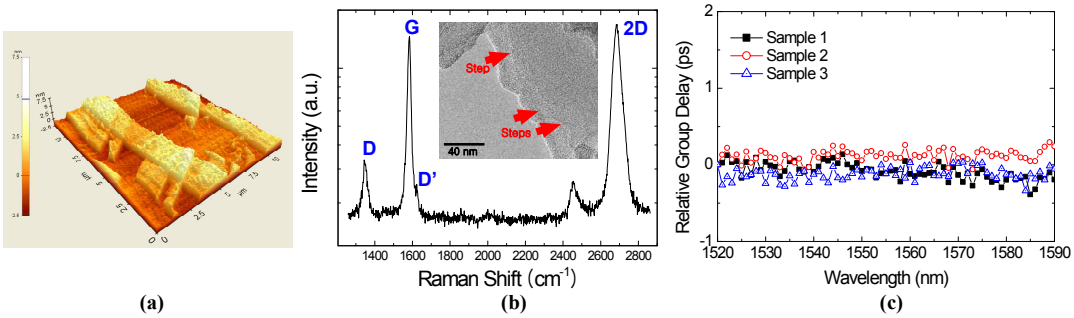

Figure 1. (a) AFM analysis on the multilayered graphene. Its 3-D image is presented. (b) Raman characterization of the physically exfoliated graphene layer. Inset shows a TEM image of the graphene. (c) Chromatic dispersion characteristics of the graphene samples, which reveal that the dispersion values are negligible.

The prepared graphene layers were analyzed with atomic force microscopy (AFM, XE-100, Park systems, scan rate of 0.5 Hz). A multilayered morphology with thicknesses that ranged from sub-nanometers (2-3 layers) to several nanometers (7-8 layers) was observed. The 3-D plot in Fig. 1(a) provides a visual insight for a morphological understanding of the multilayered graphene formed by the physical method. It was also revealed that the graphene layers with heights of 1-2 nm (3-5 layers) dominated the scanned area. Note that the AFM samples were prepared on the SiO_2 substrates using an identical method that provided graphene on the optical fiber.

The Raman analysis result is shown in Fig. 1(b). The D peak at 1350 cm^{-1} is correlated to the disorder of the crystal lattice, and the G peak at 1580 cm^{-1} is correlated to the phonon excitation at the Brillouin zone center. With the Raman analysis we presumed that the prepared samples had superior crystal quality to be applicable to photonic devices. Transmission electron microscope (TEM) image also ensures the few-layered structure of the physically prepared graphene.

The GVD property of the three graphene samples was also characterized. We prepared a high resolution GVD measurement setup based on the wavelength change-based modulation phase shift scheme. The measurement resolution was estimated to be < 5 fs/nm according to the specification of the 10-GHz network analyzer used for the measurement. A wavelength tunable laser was used for the optical source. The laser was modulated by the 10-GHz RF signal from the network analyzer, and then the modulated light was fed into a graphene sample under the test. The transmitted light from the sample was then converted back into an electrical signal using a photodetector and coupled into the input port of the network analyzer. While changing the wavelength of the laser beam from 1520 nm to 1590 nm, the relative phase (group delay) change of the transmitted light was measured using the network analyzer. Fig. 1(c) shows the measured relative group delay of the three graphene samples as the function of the laser wavelength. It is clearly evident from the graph that all the graphene samples have negligible GVDs.

3. Experimental Results for Fiber Laser Mode Locking

In order to verify the applicability of the taping-exfoliated graphene samples to the mode-locking of a fiber laser, a ring cavity configuration was constructed as shown in Fig. 2. The cavity was composed of a 5-m-long erbium doped fiber (EDF), a 980/1550 nm wavelength division multiplexer (WDM), an isolator incorporated 1480/1550 nm WDM, a 90:10 coupler, and a polarization controller. The EDF was pumped under a bidirectional pumping scheme to obtain a sufficient gain. A 980 nm pump laser diode (LD) was used for the forward pumping, whereas a 1480 nm LD was used for the backwards pumping. A polarization controller (PC) was inserted to control the polarization state of the oscillating beam within the cavity. A graphene sample under test was located after the 1480/1550 nm WDM and the output from the cavity was extracted through a 90:10 coupler.

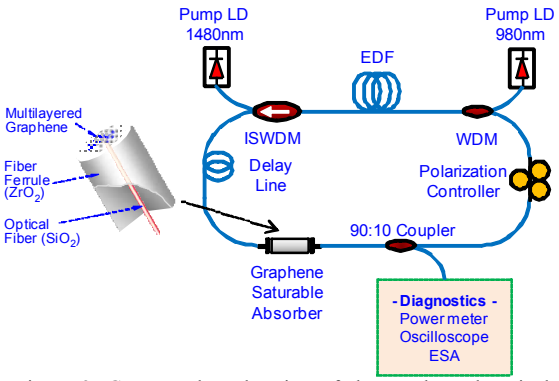

Figure 2. Conceptual explanation of the graphene-deposited fiber ferrule, and experimental setup for a passively mode-locked fiber ring laser and.

Since the GVD values of all the three graphene samples were almost negligible, we simply compensated the normal GVD of the EDF by adjusting the length of the standard single mode fiber (SMF) pigtails of the passive components used. The cavity's GVD was estimated to be ~184 fs/nm, which was an anomalous value. Using a

variety of characterization methods such as measurements of optical spectra, RF spectra, and temporal oscilloscope traces we assessed the mode-locking performance of the graphene saturable absorber samples. For the three graphene samples, the laser operation was carried out with a similar pump power condition and cavity length for an operation. The forward and backward pump diodes were operated at ~100 mW at 1480 nm and ~50 mW at 980 nm, respectively. Fig. 3(a) shows the measured oscilloscope waveform traces of the output pulse trains. The pulse period was 91.7 ns and the repetition rate was 10.9 MHz, which was coincident with the fundamental frequency of the implemented ring cavity. In Fig. 3(b), the optical spectra of the mode-locked lasers, which were measured in a resolution bandwidth of 0.02 nm are shown together with theoretical $\text{sech}^2(x)$ fitting curves. The 3-dB spectral bandwidths of all the three cases were ~0.8 nm. Assuming that the pulses are transform-limited solitons, the output pulse widths for the cases were ~3.2 ps. The output power of the mode-locked laser was 4.8 dBm irrespective of the graphene samples used. The RF spectra of the output pulses, which were measured under a resolution bandwidth of 300 Hz is shown in Fig. 3(c). The fundamental repetition rate and the peak-to-background ratio were ~10.92 MHz and ~40 dB, respectively for all the tree cases.

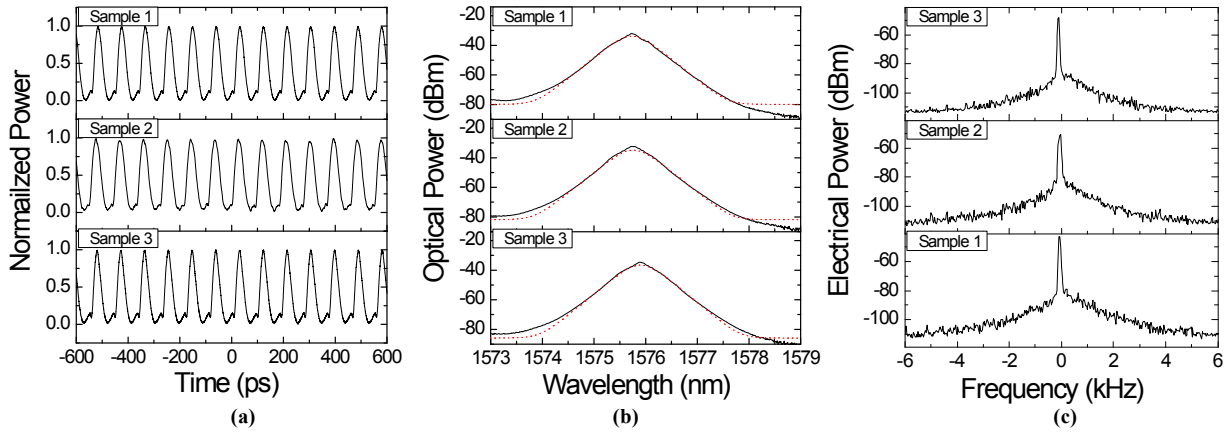

Fig. 3. (a) Measured oscilloscope waveform traces, (b) optical spectra, and (c) RF spectra of the output pulse trains of samples

4. Conclusion

We have experimentally investigated the feasibility of using a graphene sample that has been prepared by a taping exfoliation method for passive mode-locking. By constructing a passive mode-locked erbium-doped fiber laser, which incorporated a graphene as a saturable absorber, the nonlinear intensity modulating property of the taping-exfoliated graphene was investigated and the passive laser mode-locking was successfully achieved. The reproducibility of the samples was also confirmed by iterating the same mode-locking experiments using three taping-exfoliated graphene samples. We conclude that the physically exfoliated graphene samples can readily be applied for fiber laser mode-locking with dramatic enhancement on the efficiency of graphene preparation.

5. Reference

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